On the interpretation of IceCube cascade events in terms of the Glashow resonance

Atri Bhattacharya* and Raj Gandhi[†]
Harish-Chandra Research Institute, Chhatnag Road, Jhunsi, 211019 Allahabad, India

Werner Rodejohann[‡] and Atsushi Watanabe[§]

Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

The IceCube experiment (IC) has recently observed 2 cascade events with energies between 1 and 10 PeV. This energy combined with the fact that no muon-track events are observed may be interpreted as a cosmogenic $\bar{\nu}_e$ interacting in IC via the Glashow resonance (GR) $\bar{\nu}_e e \to W^- \to$ (hadrons or $\bar{\nu}_e e$). We point out a unique, background-free signature of the GR, a single isolated muon unaccompanied by any shower activity from the interaction $\bar{\nu}_e e \to W^- \to \bar{\nu}_\mu \mu^-$, and propose it as a test of this interpretation. We calculate the event numbers and find that a single such event is expected over about a three-year period in IC. We also show that, if event rates remain at their current levels then, even with the GR, standard cosmogenic fluxes cannot easily explain the observations. Moreover, if muon-tracks remain conspicuous by their absence, then new physics needs to be invoked. As example scenarios in conformity with the observations, we calculate event rates for neutrino decay and Lorentz-invariance violation.

INTRODUCTION

Observation of ultra high energy neutrinos would be an important step towards identifying the origin of cosmic rays and understanding the physics of nature's most powerful accelerators. After decades of pioneering work [1], the IceCube detector [2] is currently the most sensitive tool to study this problem. Interestingly, two high energy events, with energy in the range of 1 to 10 PeV, have recently been reported, with an expected atmospheric background of 0.14 events [3]. They are cascade events, implying that they could be caused by a) ν_e or ν_{τ} interacting with nucleons (N) via charged current (CC) interactions, or, b) ν_{α} ($\alpha = e, \mu, \text{ or } \tau$) interacting with N via neutral current (NC) interactions. A $\nu_{\mu}N$ CC interaction would have been accompanied by a long charged muon-track, which is not seen. Similarly, a $\nu_{\tau}N$ CC interaction at these energies would have been accompanied by a "double-bang" [4]. Since CC interaction cross sections at these energies are typically higher than NC cross sections by a factor of about 2.5, an interpretation via a) is favoured.

Given the present strong constraints on fluxes below 1 PeV from IceCube, any future observation in the range 1-10 PeV would likely be due to the Glashow resonance [5], involving the interaction $\bar{\nu}_e e \to W^-$, where the W^- decays mainly to electrons and hadrons, thus creating cascade events. The required resonant energy is $E=m_W^2/(2m_e)\simeq 6.3$ PeV, in the right ballpark visavis the two IceCube events. At energies close to the resonance, the cross section $\bar{\nu}_e e \to \text{anything}$ is about 350 times the standard CC interaction, $\nu_\mu N \to \text{anything}$, while the cross section for $\bar{\nu}_e e \to \text{hadrons}$ is about 240 times the standard CC value. It is for these reasons that the GR is an important factor in interpreting any observed event in the region 1-10 PeV [6]. The GR is also characterised by a unique and essentially background-

free signature (the "pure muon" [6]), which, although suppressed, may be observable over a three-year period in IC as discussed below. These pure, or contained, and isolated muons occur when the resonantly produced $W^$ decays into a muon. Hence only a contained muon-track (and nothing else) is seen inside the detector. Unlike $\nu_{\mu}N$ CC scattering, there is no shower activity, and therefore it is easily distinguishable from "standard" events. We will extract the necessary flux of $\bar{\nu}_e$ to generate two events, and apply this number to predict the expected number of "pure muons". Since pure muons are essentially background-free, even the small number of 0.34 events per year that we find, indicates that in 10 years three or four such events at E = 6.3 PeV can be expected and serve both as a straightforward test of the GR interpretation of IC's two events, as well as provide a unique physical signature of this important but as yet undetected Standard Model physics.

In general, neutrino fluxes from energetic astrophysical sources like active galactic nuclei and gamma-ray bursts are expected to have a significant $\nu_{\mu} + \bar{\nu}_{\mu}$ component which would manifest itself in the form of long muontracks in IC. So far, IC has not reported any observation of such events at energies around the range spanned by the reported cascade events. If indeed, further data gathering and analysis confirms that they are absent or suppressed in the 1-10 PeV range and above it, then this would indicate that the incoming neutrino flavour composition has a large $\bar{\nu}_e/(\nu_\mu + \bar{\nu}_\mu)$ ratio. A natural source of mainly electron-antineutrinos are cosmogenic neutrinos [7, 8], which at energies between 1–10 PeV are indeed dominated by $\bar{\nu}_e$ created in neutron decay. This interpretation of the two IC events has been put forward in Ref. [9], and we investigate it further in this letter both qualitatively and quantitatively. We find that typical fluxes in the literature have to be scaled up to conform to the observations. As at higher energy the cosmogenic neutrinos contain significant fraction of muon-neutrinos, we evaluate the implied event numbers for muon-track events using several typical fluxes for cosmogenic neutrinos. These rates lie within the present sensitivity of IC (red curve in Fig. 1) and should be observable in the near future as more data gathering and analysis is done.

If indeed, muon events continue to remain unobserved at energies between 10^7-10^{11} GeV, where they are expected to dominate in the case of cosmogenic fluxes, new physics may need to be invoked to account for their absence. We find that if neutrinos decay on their journey to Earth, and if the normal mass ordering is realized, then the $\stackrel{(-)}{\nu_e}$ fluxes dominate over the $\stackrel{(-)}{\nu_\mu}$. In contrast, for an inverted mass ordering the ν_e and $\bar{\nu}_e$ are heavily suppressed. Additionally, we show that tiny amounts of Lorentz violation could again lead to muon neutrinos ($\nu_\mu + \bar{\nu}_\mu$) being suppressed compared to electron neutrinos ($\nu_e + \bar{\nu}_e$).

In the following section we recapitulate the physics of the GR and its consequences for IC.

ICECUBE AND THE GLASHOW RESONANCE

We shall assume in this note that the two events at IC are generated by the Glashow resonance, $\bar{\nu}_e e \to W^- \to$ (hadrons or $\bar{\nu}_e e$). It is straightforward to evaluate the flux needed at these energies that leads to two shower events due to the resonance at IC. They were observed during the IC designated 2011–2012 86 string period which had a live time of 353.67 days [3]. Hence, we assume an exposure period of 1 km³-yr in our calculations. The event rate is [6]

Rate
$$(\bar{\nu}_e e \to \text{hadrons}) = 2\pi \frac{10}{18} N_A V_{\text{eff}}$$

 $\times \int dE_{\nu} \int_0^1 dy \, \frac{d\sigma}{dy} (\bar{\nu}_e e \to \text{hadrons}) \, \Phi_{\bar{\nu}_e}(E_{\nu}) \,, \quad (1)$

where $N_A = 6.022 \times 10^{23} \, \mathrm{cm}^{-3}$, $V_{\mathrm{eff}} \approx 1 \, \mathrm{km}^3$, and the factor 10/18 takes into account the number of electrons in water per unit volume. The events are integrated over the upper half sphere since up-moving $\bar{\nu}_e$ at these energies are attenuated by Earth matter. We find

$$E^2 \Phi_{\bar{\nu}_e}(E_{\nu})|_{E_{\nu}=6.3 \text{ PeV}} = 7.6 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$
(2)

This value is in a region that will be within the reach of IC's detection as it collects more data.

Should the two events indeed be a result of the GR, it will be the first observation a) of the Glashow resonance, and b) of extra-galactic neutrinos. Therefore, it is important to confirm whether the observed events are indeed due to this process. One way to check this experimentally would be to look at the number of "pure muon" and "contained tau track" events generated as a result of the

related processes $\bar{\nu}_e e \to \bar{\nu}_\mu \mu$ and $\bar{\nu}_e e \to \bar{\nu}_\tau \tau$ respectively, which accompany the GR hadronic interaction and occur when the resonant W^- decays to a muon or tau instead of hadrons [6]. Such pure muon events would be clearly distinguishable from the muon-track events coming from the neutrino-nucleon interactions because, originating in a leptonic interaction, these would not have the characteristic accompanying hadronic shower. The cross section for this process is related to the one to generate hadrons by $\Gamma_{W\to\bar{\nu}_{\mu}\mu}/\Gamma_{W\to\text{hadrons}}\approx 0.156$. Thus the event rate is small but distinctive in signature. With the flux $\Phi_{\bar{\nu}_e}$ obtained in Eq. (2) we can estimate the pure muon event rate at E = 6.3 PeV as 0.34 per year, leading to a single event over a span of about three years. However, the "smoking-gun" nature of these signals, and the fact that the background (from $\nu_{\mu}e \rightarrow \nu_{e}\mu$ interactions) is negligible [10], makes them a significant tool for GR detection and confirmation in spite of the small rates.

The next step is to consider sources of high energy neutrinos responsible for the GR events. Diffuse fluxes with a typical power law will have roughly equal ν_{μ} and ν_{e} content when reaching Earth, and one should expect at energies below PeV a sizable number of muon-track events, which however, so far, have not been seen. It is a useful exercise, therefore, to find neutrino sources circumventing the problem. We will show in the next section that cosmogenic neutrinos are natural candidates for this.

COSMOGENIC NEUTRINOS

In this section we shall assume that the origin of the electron-antineutrinos is cosmogenic [7, 8], *i.e.*, generated by interactions of cosmic ray protons with the cosmic microwave photons, creating a Δ resonance:

$$p\gamma \to \Delta^+ \to \pi^+ n$$
. (3)

At the low energies, E < 100 PeV, the resulting flux is dominated by the neutron decay, and hence

$$\Phi^0_{\bar{\nu}_e}: \Phi^0_{\bar{\nu}_\mu}: \Phi^0_{\bar{\nu}_\tau} = 1:0:0 \text{ and } \Phi^0_{\nu_\alpha} = 0,$$
(4)

is the initial flavour composition. Here α represents all flavours of the neutrino spectrum. Lepton mixing will modify this flux decomposition, and at Earth we have $\Phi_{\nu_{\alpha}} = P_{\alpha\beta} \Phi^{0}_{\nu_{\beta}}$, where the neutrino mixing probability is $P_{\alpha\beta} = \sum |U_{\alpha i}|^2 |U_{\beta i}|^2$, with U being the lepton mixing matrix. Inserting the current best-fit values of the oscillation parameters from Ref. [11], it turns out that the (1:0:0) flux composition is transferred to (0.55:0.25:0.20). Within 3σ ranges of the oscillation parameters, the maximal value of the ratio $\Phi_{\bar{\nu}_e}/\Phi_{\bar{\nu}_{\mu}}$ is 4.65.

Detailed studies of the spectrum of cosmogenic neutrinos arriving at Earth have been made in the literature, and we use the one calculated in Ref. [7] (ESS) to see if it can explain the events seen at IC. We normalise this flux so that the $\bar{\nu}_e$ flux at ~ 10 PeV produces the two events at IC over the appropriate exposure. This requires scaling the $\bar{\nu}_e$ flux, and consequently the fluxes of all flavours, up by a factor of about 300 from those obtained in Ref. [7]. At higher energies, i.e. $10^8 - 10^{10}$ GeV, the decay chain $\Delta^+ \to \pi^+ n \to e^+ p e \nu_e \bar{\nu}_e \bar{\nu}_\mu \nu_\mu$ causes a significant bump in the fluxes of the electron and muon neutrinos, and muon antineutrinos. As a result, there will be a significant number of shower and muon-track events observed at IC at these energies. Thus, with these fluxes, IC should see about 15 muon-track standard CC events per year in the energy range $10^7 - 10^9$ GeV, and about 11 similar events over energies $10^9 - 10^{11}$ GeV.

For comparison, we have carried out similar event rate calculations using a different prediction for the cosmogenic neutrino flux [8]. With the FRII flux spectra described therein, we find that IC should have seen 2.2 shower events, and 3.8 muon-track events per year in the energy range $10^5 - 10^7$ GeV.

Evidently, if the CC muon-tracks are not observed in the near future, then it will clearly be difficult to reconcile the observation of the two shower events at PeV energies with the lack of characteristic muon-track events at higher energies using cosmogenic neutrinos. However, if we allow for the effect of non-standard physics during the propagation of the neutrinos from source to Earth, it might be possible to suppress the muon neutrino flux while keeping the $\bar{\nu}_e$ flux unchanged. If this suppression is sufficient, it would nicely reconcile the observation of shower events with the lack of muon-track events. In the following section we investigate two scenarios which allow this: neutrino decay and Lorentz-invariance violation.

NON-STANDARD PHYSICS

Neutrino decay. Assuming that neutrinos produced at the source decay such that only the lightest mass state survives, the flux composition reaching Earth is [12]:

$$(\Phi_e : \Phi_u : \Phi_\tau) = (|U_{ei}|^2 : |U_{ui}|^2 : |U_{\tau i}|^2), \qquad (5)$$

where $\Phi_{\alpha} = \Phi_{\nu_{\alpha}} + \Phi_{\bar{\nu}_{\alpha}}$ and either i=1 or 3, depending on the normal or inverted mass ordering. In case of the inverted ordering, since $|U_{e3}|^2 \simeq 0.02 \ll |U_{\mu,\tau 3}|^2 \simeq \frac{1}{2}$, the muon-neutrino flux will dominate and we will run into problems with non-observation of muon-tracks. Hence we are led to consider the normal mass ordering [13]. With the present best-fit values of the mixing parameters, one obtains $\Phi_e/\Phi_{\mu}=5.32$. Thus, when the fluxes are scaled so that the $\bar{\nu}_e$ flux at PeV energies explains the two shower events seen at IC, the induced suppression of the $\nu_{\mu} + \bar{\nu}_{\mu}$ flux at higher energies leads to about

4.9 events per year. Varying the neutrino mixing parameters over their allowed 3σ range, we find that the maximum suppression of the muon neutrino flux with respect to the electron neutrino flux can be $\Phi_e/\Phi_\mu=20.96$, when $\theta_{12}=30.59^\circ$, $\theta_{23}=52.96^\circ$, $\theta_{13}=10.19^\circ$ with $\delta_{CP}=180^\circ$. With the ESS fluxes scaled as explained in the previous section, but with the corresponding muon fluxes suppressed by this factor, the number of muontrack events expected in the energy range 10^7-10^{11} GeV reduces to about 1.3 per year. Assuming these optimistic values of the mixing parameters, we see that it is possible to obtain a marginally consistent picture (see Fig. 1a): explaining the two shower events at PeV energies via the GR mechanism and sufficiently suppressing any muontrack events.

Effect of Lorentz-invariance violation (LV). Violations of Lorentz-invariance might show up at low energies as a tiny effect in neutrino oscillation [14]. To simplify the analysis of LV, we study a model where it affects the oscillation of only ν_{μ} and ν_{e} . The effective Hamiltonian in the mass basis is modified to

$$H_{\text{eff}}(\alpha) = \begin{pmatrix} \frac{m_1^2}{2E} & \alpha\\ \alpha & \frac{m_2^2}{2E} \end{pmatrix}, \tag{6}$$

which gives an oscillation probability of $P[\nu_e \rightarrow \nu_\mu]$ $\frac{1}{2}\sin^2 2\theta_{12}\left(1-\frac{\alpha^2}{\Omega^2}-\frac{\omega^2}{\Omega^2}\cos(2\Omega L)\right)$, where $\omega=\frac{m_2^2-m_1^2}{4E}$ and $\Omega = \sqrt{\omega^2 + \alpha^2}$. Here α is the LV parameter with dimensions of energy, and we have only retained the leading α order correction to the probability. The effect of LV with various values of α is shown in Fig. 1b. Clearly, even with tiny values of the LV parameter, enough suppression of the ν_{μ} flux with respect to the ν_{e} flux can be achieved to evade future IC bounds on the muon-track events. For example, with $\alpha = 10^{-29}$ GeV, about 0.18 muon-track events are expected over energies $10^7 - 10^{11}$ GeV per year, which implies that IC would only be able to observe a single such event over 5.5 years of exposure. Such a suppression can, therefore, explain the lack of muon-track events at high energies, while still leaving the $\bar{\nu}_e$ flux at PeV energies large enough to explain the two observed shower events.

We thus conclude that with non-standard physics it is possible to explain, simultaneously, a) IC's two shower events at PeV energies (by means of the GR process involving the cosmogenic $\bar{\nu}_e$), and b) the non-observation of muon-track events at the same detector at higher energies.

CONCLUSIONS

The Glashow resonance is an important Standard Model process which should be considered in any interpretation of IceCube events seen in the energy range

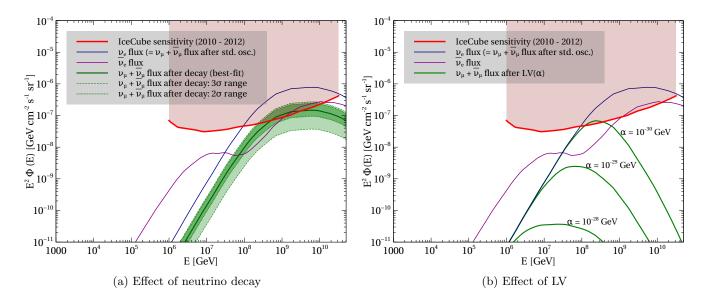


FIG. 1: The effect of non-standard physics, neutrino decay and LV (as a function of the LV parameter α), on the ν_{μ} and $\bar{\nu}_{\mu}$ ESS fluxes. The fluxes have all been appropriately scaled so that the $\bar{\nu}_{e}$ flux at 6.3 PeV explains the two shower events observed at IC. The total $\nu_{\mu} + \bar{\nu}_{\mu}$ flux, when affected only by standard oscillation, is identical to the ν_{e} flux shown here. For the decay scenario, the range of variation of the ν_{μ} and $\bar{\nu}_{\mu}$ flux as the oscillation parameters vary over the 2σ and 3σ range is also shown. The projected sensitivity of IC, in the case of a null-event result during the period 2010–2012, is indicated by the red line.

 $10^6-10^7~{\rm GeV}$. It has a unique and background-free signature, the pure muon, which can be a smoking gun for this process. Natural candidates for neutrinos at these (and higher) energies are cosmogenic neutrinos. We have shown that standard fluxes, which have to be scaled by an (unexplained) factor of 300, do not explain IC's two events, since charged current generated muon-track events are not seen. While both the need for scaling the flux up and the paucity of muon-tracks may change as IC collects and analyses new data, we have pointed out that the present observations may, however, be understood by invoking the advent of non-standard physics during propagation. We have demonstrated this with explicit examples of neutrino decay and Lorentz invariance violation.

We thank Francis Halzen, Aya Ishihara and John Learned for very useful discussions. WR is supported by the Max Planck Society through the Strategic Innovation Fund and by the DFG in the project RO 2516/4-1, AW by the Young Researcher Overseas Visits Program for Vitalizing Brain Circulation Japanese in JSPS. AB and RG acknowledge the support from the DAE XI Plan Neutrino project.

- § atsushi.watanabe@mpi-hd.mpg.de
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^{*} atri@hri.res.in

[†] nubarnu@gmail.com

[‡] werner.rodejohann@mpi-hd.mpg.de